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Accreting Isolated Neutron Stars

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Abstract. Accretion of interstellar material by a magnetized, slowly rotating isolated neutron star is discussed. We show that the average persistent X-ray luminosity of these objects is unlikely to exceed $4 \times 10^{26}\,\mathrm{erg\,s^{-1}}$. They can also appear as X-ray bursters with the burst duration of ~ 30 minutes and repetition time of $\sim 10^5$ yr. This indicates that the number of the accreting isolated neutron stars which could be observed with recent X-ray missions is a few orders of magnitude smaller than that previously estimated. Our findings argue against models in which the magnetic field of neutron stars is assumed to decay exponentially on a time scale shorter than 500 Myr.

1. Introduction

As shown first by Ostriker et al. (1970) and Shvartsman (1971) an old isolated neutron star moving through the interstellar medium is able to capture material with a rate of

$$\dot{\mathfrak{M}}_{\rm c} \simeq 10^9\,\mathrm{g\,s^{-1}} \;\times\; n\,m^2 \left(\frac{V_{\rm rel}}{10^7\,\mathrm{cm\,s^{-1}}}\right)^{-3}. \qquad (1)$$

Here m is the mass of the neutron star expressed in units of $1.4\,M_{\odot}$, n is the number density of the interstellar material expressed in units of 1 hydrogen atom $\mathrm{cm^{-3}}$ and $V_{\rm rel}$ is the relative velocity between the star and its environment, which is limited to the sound speed in the interstellar material as $V_{\rm rel} > V_{\rm s} \simeq 10^6\,\mathrm{cm\,s^{-1}}$. If all the captured material were accreted onto the stellar surface the star would appear as an X-ray source of a luminosity

$$L_{\rm x} \lesssim L_0 \simeq 10^{29}\,\mathrm{erg\,s^{-1}} \;\times\; m\,r_6^{-1}\,(\dot{\mathfrak{M}}_{\rm a}/\dot{\mathfrak{M}}_{\rm c}), \qquad (2)$$

where r_6 is the radius of the neutron star expressed in units of 10^6 cm and the parameter $\dot{\mathfrak{M}}_{\rm a}$ denotes the mass accretion rate onto the stellar surface, which in the general case can differ from the mass capture rate by the star from its environment, $\dot{\mathfrak{M}}_{\rm c}$. Combining this finding with currently established spatial and velocity distributions of neutron stars one could expect about 3×10^4 such sources to be detected by *Chandra* and XMM-*Newton* (for a discussion see, e.g., Popov et al. 2000a). However, none of them has been identified so far.

A lack of success in searching for the accreting isolated neutron stars indicates that either the value of $\dot{\mathfrak{M}}_{\rm c}$ is significantly smaller than that evaluated from Eq. (1) or there is an additional factor which prevents the interstellar material from reaching the stellar surface. The first possibility has been critically discussed and basically discarded by Perna et al. (2003). Among factors which have not been taken into account in the above accretion scenario is the magnetic field of the neutron star. A zero-field approximation appears to be reasonable only if the dipole magnetic moment of an isolated neutron star is $< 10^{22}\,\mathrm{G\,cm^3}$ (the corresponding surface field is $\sim 10^4$ G). Under this condition a formation of the magnetosphere which could prevent the captured material from reaching the stellar surface does not occur. If, however, the surface field significantly exceeds 10 kG the influence of the stellar magnetic field on the accretion picture has to be taken into account. As we show the expected X-ray luminosity of accreting isolated neutron stars in this case proves to be significantly smaller than that estimated by Eq. (2).

2. Magnetic field strength and spin period

A necessary condition for the captured material to reach the surface of a magnetized, neutron star rotating with a period $P_{\rm s}$ is

$$r_{\rm m} < r_{\rm cor}, \qquad (3)$$

where

$$r_{\rm m} \simeq 6 \times 10^{10}\,\mathrm{cm} \;\times\; \mu_{30}^{4/7}\;\dot{\mathfrak{M}}_9^{-2/7}\;m^{-1/7}, \qquad (4)$$

is the magnetospheric radius of a neutron star, and

$$r_{\rm cor} \simeq 1.7 \times 10^8\,\mathrm{cm} \;\times\; m^{1/3}\;P_{\rm s}^{2/3} \qquad (5)$$

is its corotational radius. Here μ_{30} is the dipole magnetic moment of the star expressed in units of $10^{30}\,\mathrm{G\,cm^3}$ and $\dot{\mathfrak{M}}_9 = \dot{\mathfrak{M}}_{\rm c}/10^9\,\mathrm{g\,s^{-1}}$. Solving the inequality (3) for $P_{\rm s}$ one finds

$$P_{\rm s} > P_{\rm cd} \simeq 7000\ \mathrm{s} \;\times\; \mu_{30}^{6/7} V_7^{9/7} n^{-3/7} m^{-11/7}, \qquad (6)$$

where $V_7 = V_{\rm rel}/10^7\,\mathrm{cm\,s^{-1}}$. This implies that the spin-down rate of the neutron star in a previous epoch was

$$\dot{P} > 10^{-14} \left[\frac{P_{\rm s}}{7000\,\mathrm{s}}\right] \left[\frac{t_{\rm sd}}{10^{10}\,\mathrm{yr}}\right]^{-1} \mathrm{s\,s^{-1}}, \qquad (7)$$

and therefore, suggests that only the stars with initial dipole magnetic moment in excess of $10^{29}\,\mathrm{G\,cm^3}$ could be a subject of further consideration (for a discussion see, e.g., Popov et al. 2000b). Here t_{sd} is the spin-down timescale of the neutron star.

3. Accretion flow geometry

For an accretion disk around a magnetized isolated neutron star to form the relative velocity should satisfy the condition $V_{\mathrm{rel}} < V_0$, where

$$V_0 \simeq 10^5\ \mathrm{cm\,s^{-1}}\ \times\ \mu_{30}^{-6/65} n^{3/65} m^{5/13}\ \times \quad (8)$$
$$\left(\frac{V_{\mathrm{t}}}{10^6\,\mathrm{cm\,s^{-1}}}\right)^{21/65} \left(\frac{R_{\mathrm{t}}}{10^{20}\,\mathrm{cm}}\right)^{-7/65}.$$

Here V_{t} is the velocity of turbulent motions of the interstellar material at a scale of R_{t} and the Kolmogorov spectrum of the turbulent motions is assumed (Prokhorov et al. 2002). This inequality, however, is unlikely to be satisfied since V_0 is smaller than the speed of sound in the interstellar material, and therefore, is smaller than the lower limit to V_{rel}.

Thus, the accretion by old isolated neutron stars can be treated in terms of a spherical (Bondi) accretion onto a magnetized, slowly rotating neutron star. The accretion picture under these conditions has been reconstructed first by Arons & Lea (1976) and Elsner & Lamb (1976) and further developed by Lamb et al. (1977) and Elsner & Lamb (1984). An application of the results reported in these papers to the case of an isolated neutron star is discussed in the following section.

4. Accretion flow at r_{m}

As shown by Arons & Lea (1976) and Elsner & Lamb (1976), the magnetosphere of a neutron star undergoing spherically symmetrical accretion is closed and, in the first approximation, prevents the accretion flow from reaching the stellar surface. The mass accretion rate onto the stellar surface is therefore limited to the rate of plasma entry into the magnetosphere. The fastest modes by which the material stored over the magnetospheric boundary can enter the stellar field are the Bohm diffusion and interchange instabilities (Elsner & Lamb 1984).

The rate of plasma diffusion in the case considered can be evaluated as (Ikhsanov 2003)

$$\dot{\mathfrak{M}}_{\mathrm{B}} \leq 2\times 10^6\,\mathrm{g\,s^{-1}}\ \zeta_{0.1}^{1/2}\ \mu_{30}^{-1/14}\ m^{15/7}\ n^{11/14}\ V_7^{33/14}, \quad (9)$$

where $\zeta_{0.1} = \zeta/0.1$ is the efficiency of the diffusion process normalized according to Gosling et al. (1991). This indicates that the luminosity of the diffusion-driven source is limited to

$$L_{\mathrm{x,dd}} \leq 4\times 10^{26}\,\mathrm{erg\,s^{-1}}\ \times \quad (10)$$
$$\zeta_{0.1}^{1/2}\ \mu_{30}^{-1/14}\ m^{22/7}\ n^{11/14}\ V_7^{33/14}\ r_6^{-1}.$$

For the material to enter the stellar magnetic field with the rate $\sim \dot{\mathfrak{M}}_{\mathrm{c}}$ the boundary should be interchange unstable. The onset condition for the instabilities is (Arons & Lea 1976; Elsner & Lamb 1976)

$$T_{\mathrm{p}}(r_{\mathrm{m}}) \leq 0.1 T_{\mathrm{ff}}(r_{\mathrm{m}}), \quad (11)$$

where $T_{\mathrm{p}}(r_{\mathrm{m}})$ and $T_{\mathrm{ff}}(r_{\mathrm{m}})$ are the plasma temperature and the free-fall (adiabatic) temperature at the magnetospheric boundary, respectively. This indicates that a direct accretion of the captured material onto the stellar surface could occur only if the cooling of the plasma at the boundary dominates the heating.

The mechanism which is responsible for the cooling of plasma at the boundary is the bremsstrahlung emission. Indeed, the free-fall temperature and number density of the material stored over the boundary are, respectively,

$$T_{\mathrm{ff}}(r_{\mathrm{m}}) \simeq\ 10^7\,\mathrm{K}\ \times\ \mu_{30}^{-4/7} \dot{\mathfrak{M}}_9^{2/7} m^{6/7}, \quad (12)$$

$$N_{\mathrm{e}}(r_{\mathrm{m}}) \simeq 300\,\mathrm{cm^{-3}}\ \times\ \mu_{30}^{-6/7} \dot{\mathfrak{M}}_9^{10/7} m^{-2/7}. \quad (13)$$

Under these conditions both the cyclotron and Compton cooling time scale are significantly larger than the bremsstrahlung cooling time scale

$$t_{\mathrm{br}}(r_{\mathrm{m}}) \simeq 10^5\,\mathrm{yr}\ \times\ T_7^{1/2} \left(\frac{N_{\mathrm{e}}(r_{\mathrm{m}})}{300\,\mathrm{cm^{-3}}}\right)^{-1}, \quad (14)$$

where $T_7 = T_{\mathrm{ff}}(r_{\mathrm{m}})/10^7\,\mathrm{K}$.

The heating of the material at the magnetospheric boundary is governed by the following processes.

4.1. Adiabatic shock

As the captured material reaches the boundary it stops in an adiabatic shock. The temperature in the shock increases to $T_{\mathrm{ff}}(r_{\mathrm{m}})$ on a dynamical time scale,

$$t_{\mathrm{ff}}(r_{\mathrm{m}}) \simeq 740\,\mathrm{s}\ \times\ m^{-1/2} \left(\frac{r_{\mathrm{m}}}{6\times 10^{10}\,\mathrm{cm}}\right)^{3/2}. \quad (15)$$

Since $t_{\mathrm{ff}}(r_{\mathrm{m}}) \ll t_{\mathrm{br}}(r_{\mathrm{m}})$ the height of the homogeneous atmosphere at the boundary proves to be $\sim r_{\mathrm{m}}$. This prevents an accumulation of material over the boundary. Furthermore, as the condition $t_{\mathrm{ff}}(r_{\mathrm{G}}) < t_{\mathrm{br}}(r_{\mathrm{m}})$ is satisfied throughout the gravitational radius of the neutron star a hot quasi-stationary envelope extended from r_{m} up to r_{G} forms (Davies & Pringle 1981). The formation of the envelope prevents the surrounding material from penetrating to within the gravitational radius of the neutron star. The mass of the envelope is, therefore, conserved. As the neutron star moves through the interstellar medium the surrounding material overflow the outer edge of the envelope with a rate of $\dot{\mathfrak{M}}_{\mathrm{c}}$.

Within an approximation of a non-rotating star whose "magnetic gate" at the boundary is closed completely the envelope remains in a stationary state on a time scale of

$t_{\rm br}(r_{\rm m})$. As the condition (11) is satisfied the boundary becomes unstable and material enters into the magnetic field and accretes onto the stellar surface with a rate of $\sim \dot{\mathfrak{M}}_{\rm c}$. As shown by Lamb et al. (1977), the time of the accretion event in this case is limited to $t_{\rm burst} <$ a few $\times t_{\rm ff}(r_{\rm m})$ during which the temperature of the envelope increases again to the adiabatic temperature (as the upper layers of the envelope come to $r_{\rm m}$). The corresponding source, therefore, would appear as an X-ray burster with the luminosity

$$L_{\rm burst} \simeq 2 \times 10^{29}\ n\ V_7^{-3}\ m^3\ r_6^{-1}\ {\rm erg\,s^{-1}}, \qquad (16)$$

the typical outburst durations of $t_{\rm burst} \leq 30$ min and the repetition time of $t_{\rm rep} \sim t_{\rm br}(r_{\rm m}) \sim 10^5$ yr.

4.2. Subsonic propeller

As shown by Davies & Pringle (1981), the rotation of a neutron star surrounded by the hot envelope can be neglected only if its spin period exceeds (Ikhsanov 2001)

$$P_{\rm br} \simeq 10^5\,{\rm s}\ \times\ \mu_{30}^{16/21} n^{-5/7} V_7^{15/7} m^{-34/21}. \qquad (17)$$

Otherwise, the heating of plasma at the inner edge of the envelope due to propeller action by the star dominates cooling. The corresponding state of the neutron star is referred to as a subsonic propeller. The star remains in this state as long as its spin period satisfies the condition $P_{\rm cd} < P_{\rm s} < P_{\rm br}$. The time during which the spin period increases from $P_{\rm cd}$ up to $P_{\rm br}$ is

$$\tau_{\rm br} \simeq 2 \times 10^5\,{\rm yr}\ \times\ \mu_{30}^{-2}\ I_{45}\ m\ \left(\frac{P_{\rm br}}{10^5\,{\rm yr}}\right), \qquad (18)$$

where I_{45} is the moment of inertia of the neutron star expressed in units of $10^{45}\,{\rm g\,cm^2}$. This indicates that the spin periods of accreting isolated neutron stars are expected to be in excess of a day, and therefore, these objects are unlikely to be recognized as pulsars.

4.3. Diffusion-driven accretor

As mentioned above, the "magnetic gate" at the magnetospheric boundary is not closed completely. The plasma flow through the interchange stable boundary is governed by the diffusion. As shown by Ikhsanov (2003), this leads to a drift of the envelope material towards the star and, as a result, to an additional energy source for heating of the envelope material. The heating due to the radial drift dominates the bremsstrahlung energy losses from the envelope if $\dot{\mathfrak{M}}_{\rm c} < \dot{\mathfrak{M}}_{\rm cr}$, where

$$\dot{\mathfrak{M}}_{\rm cr} \simeq 10^{14}\,{\rm g\,s^{-1}}\ \times\ \zeta_{0.1}^{7/17} \mu_{30}^{-1/17} V_7^{14/17} m^{16/17}. \qquad (19)$$

This indicates that only the old isolated neutron stars which move slowly ($V_{\rm rel} \ll 10^7\,{\rm cm\,s^{-1}}$) through a dense molecular cloud ($N_{\rm e} > 10\,{\rm cm^{-3}}$) can be expected to be observed as the bursters. The rest of the population would appear as persistent X-ray sources with the luminosity of $L_{\rm x} \leq L_{\rm x,dd}$ (see Eq. 10).

5. Discussion

The results of this paper force us to reconsider previous predictions about the number of old isolated neutron stars which can be observed with current X-ray missions. In particular, if the surface field strength of these objects exceeds 10 kG the total flux of their persistent X-ray emission is limited to $F < 10^{-16}\,{\rm erg\,cm^2\,s^{-1}}\,d_{100}^{-2}$, where d_{100} is the distance to the source expressed in units of 100 pc. The mean energy of the emitted photons within the blackbody approximation is close to 50 eV. This clearly shows that detection of these sources by *Chandra* and XMM-*Newton* is impossible.

The X-ray flux emitted during the outbursts (see Sect. 4.1) is over the threshold of sensitivity of modern detectors. However, the probability to detect this event appears to be negligibly small. Indeed, the number of these sources which could be detected by current X-ray missions is

$$N \leq 10^{-5} \left(\frac{N(0)}{3 \times 10^4}\right) \left(\frac{t_{\rm burst}}{30\,{\rm min}}\right) \left(\frac{t_{\rm rep}}{10^5\,{\rm yr}}\right), \qquad (20)$$

where $N(0)$ is the number of the sources which would be observed if the influence of the stellar magnetic field on the accretion flow at $r_{\rm m}$ were insignificant (Popov et al. 2000a).

Finally, if the magnetic field of an isolated neutron star were $\lesssim 10$ kG it would appear as an accretion-powered X-ray source with a luminosity of L_0 (see Eq. 2). Indeed, the state of the star under these conditions can be unambiguously identified with an accretor independently of its initial period and magnetic field strength. Furthermore, as shown by Bisnovatyi-Kogan & Blinnikov (1980) a heating of the accretion flow inside the Bondi radius is unable to reduce the mass accretion rate onto the stellar surface significantly. That is why, a lack of success in searching for the accreting isolated neutron stars indicates that the magnetic field of old neutron stars does not vanish completely, but remains at least over a level of 10 kG. This allows us to discard a situation in which the magnetic field of a neutron star dissipates exponentially on a time scale shorter that 500 Myr.

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